Simulation of ultra-thin sheet metal forming using phenomenological and crystal plasticity models

F Adzima[a,b], PY Manach[a], T Balan[b], L Tabourot[c], S Toutain[d], JL Diot[e]

[a] Univ. Bretagne Sud, CNRS FRE 3744, IRDL, Rue de Saint Maudé, F-56100 Lorient, France

[b] Arts et Métiers ParisTech, LEM3, UMR CNRS 7239, 4 rue Augustin Fresnel, 57078 Metz Cedex 3, France

[c] Université de Savoie, SYMME, EA 4144, 74944 Annecy-le-Vieux, France

[d] Delta Composants, 1 Rue Pierre Gilles de Genne, 72403 La Ferté-Bernard, France

[e] NovaPack SAS, 14 Rue des Glairaux, 38120 Saint Egrève, France

tudor.balan@ensam.eu

Abstract. Micro-forming of ultra-thin sheet metals raises numerous challenges. In this investigation, the predictions of state-of-the-art crystal plasticity (CP) and phenomenological models are compared in the framework of industrial bending-dominated forming processes. Sheet copper alloys 0.1mm-thick are considered, with more than 20 grains through the thickness. Consequently, both model approaches are valid on theoretical ground. The phenomenological models' performance was conditioned by the experimental database used for parameter identification. The CP approach was more robust with respect to parameter identification, while allowing for a less flexible description of kinematic hardening, at the cost of finer mesh and specific grain-meshing strategies. The conditions for accurate springback predictions with CP-based models are investigated, in an attempt to bring these models at the robustness level required for industrial application.

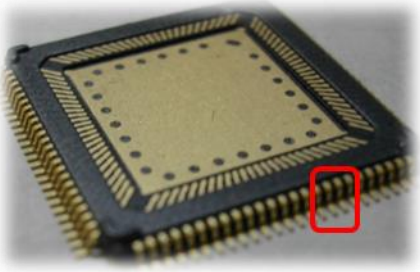
1. Introduction

The ongoing trend on device miniaturization has increased the demand for microparts. Micro-manufacturing technologies are being developed and optimized continuously to meet the needs of industry. Particularly, micro-forming processes can achieve high productivity and low costs while delivering good parts. However, the knowledge and the simulation tools that are successfully operated in macro-scaled forming cannot be applied to accelerate the design phase of micro-forming processes.

Indeed, the employed ultra-thin sheet metals exhibit peculiarities in their deformation behavior. In the present study, crystal plasticity and phenomenological material models are implemented for the numerical simulation of industrial micro-forming processes. Their predictive capabilities are compared and the influencing parameters for accurate predictions are investigated.

2. Materials and demonstrator parts

The current study focuses on two demonstrator parts manufactured from metal sheets of CuBe2 and CuFe2P copper alloys. The gull-wing microelectronic package leads (see Fig. 1 (a)) are made of 127 µm thick CuFe2P sheets while 100 µm thick CuBe2 sheets are processed to produce the connector displayed on Fig. 1 (b). Thus, due to the part geometries, small (chip lead) and large (connector) R/T (radius/thickness) ratios situations are under investigation.



(a)

(b)

Fig. 1: Demonstrator parts: (a) CuFe2P made LQFP package (small R/T ratio) and (b) CuBe2 made connector (large R/T ratio)

3. Material models and parameters

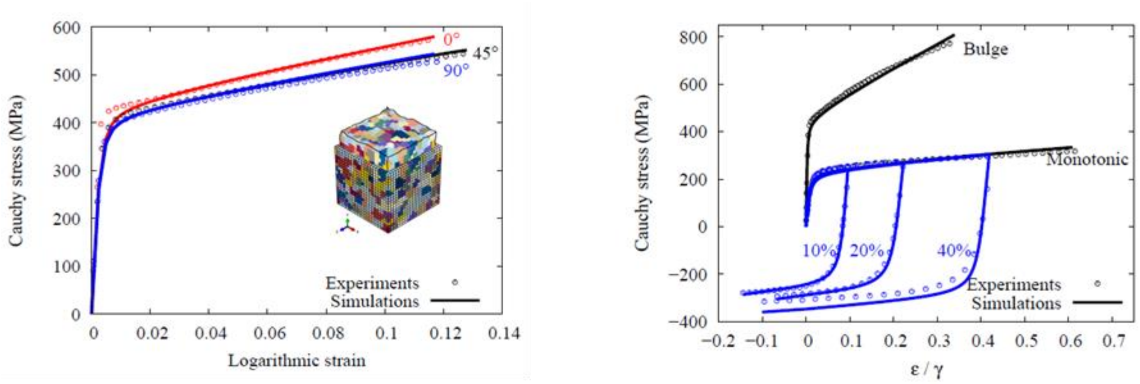
Phenomenological modeling as well as crystal plasticity based modeling are considered since there is an average of 20 grains through sheets thickness. The crystal plasticity model is based on the works of [1] and [2]. The slip rate $\dot{\gamma}^{(s)}$ on a slip system *(s)* is given by a visco-plastic law as a function of the resolved shear stress on the system $\tau^{(s)}$ and its resistance to motion $\tau_c^{(s)}$, reading

$$\dot{\gamma}^{(s)} = \begin{cases} \dot{\gamma}_0^{(s)} \; sign(\tau^{(s)}) \left| \frac{\tau^{(s)}}{\tau_c^{(s)}} \right|^n & \text{if } \left|\tau^{(s)}\right| \geq \tau_c^{(s)} \\ 0 & \text{if } \left|\tau^{(s)}\right| < \tau_c^{(s)} \end{cases} \tag{1}$$

In the previous equation, $\dot{\gamma}_0^{(s)}$ is the reference strain rate and *n* is the strain rate sensitivity coefficient. The hardening at slip system level is based on the so-called PAN (Peirce-Asaro-Needleman) model [1].

The phenomenological plasticity model is elastic-visco-plastic and accounts for material anisotropy through the yield function of Bron and Besson [3]. Mixed hardening is assumed with an isotropic hardening of Hockett-Sherby and a combined Armstrong-Frederick & Prager kinematic hardening. The phenomenological and crystal plasticity approaches were implemented in ABAQUS/Standard.

The sheets behavior was characterized through mechanical tests and a large experimental database was established. The latter consisted of tensile tests in 0, 45 and 90° to the rolling direction (R.D.), equi-biaxial loading via hydraulic bulge test, monotonic shear tests and reversed shear tests after different pre-strain levels. The crystal plasticity model was calibrated on the tensile test in the R.D. on a Representative Volume Element which grains orientations were sampled from EBSD measurements. As illustrated on Fig. 2, the CPFEM (crystal plasticity finite element method) model proved capable of providing good predictions of all experimental tests although it was calibrated on a single tensile test.



(a) (b)

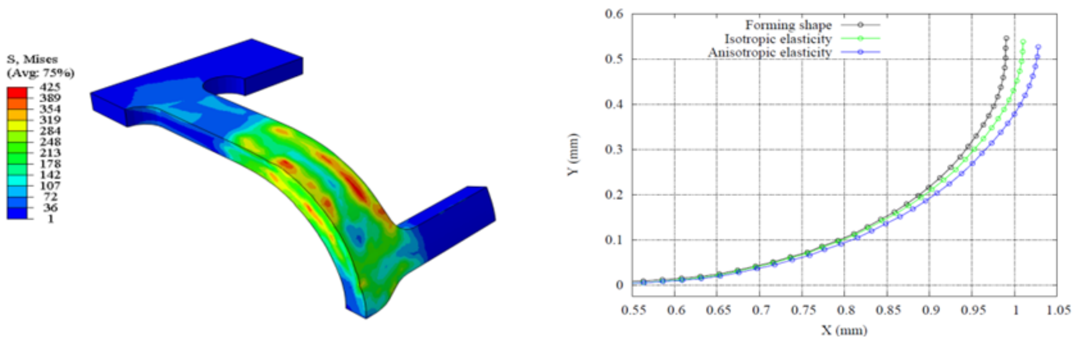
Fig. 2: Predictions by the CPFEM model of (a) tensile tests and (b) shear and bulge tests

On the other hand, the phenomenological plasticity model required a calibration procedure, implemented in SiDoLo [4], on the full database in order to describe accurately all the experimental strain paths.

4. Springback predictions and influencing parameters

The two modeling approaches (CPFEM and phenomenological) were applied to the prediction of springback in bending processes. A numerical study was conducted on several parameters of the CPFEM model. Both demonstrator parts were employed in the study.

Crystalline elastic anisotropy was found to significantly impact the CPFEM predictions of springback shapes. Indeed, assuming whether isotropic or anisotropic elasticity yielded very little difference in the forming step as anisotropic discrete slip flow drives the mechanical response in both cases. However, springback is dominated by the elastic behavior and thus affected by the type of elasticity considered. The differences that arise are illustrated on Fig. 3 which represents the profiles of a portion of the connector part.



(a) (b)

Fig. 3: Influence of elastic anisotropy on the profile (b) of a portion of the formed connector (a)

Furthermore, the ratio T/D (sheet thickness over grain diameter) which can be approximated to the number of grains in the thickness was linked to the amount of springback predicted. When this ratio and consequently the number of grains of grains in the part were increased, the predicted mechanical response converged towards the prediction of the phenomenological model. The CPFEM springback angle also grew closer to the phenomenological value and the experimental measurements (see Fig. 4).

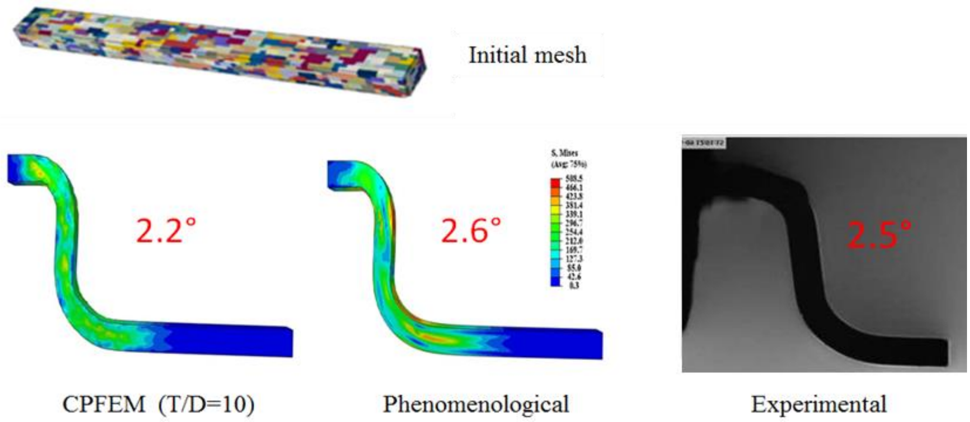


Fig. 4: Predictions and measurement of the springback angle of the chip leads

A similar trend on the evolution of springback with the T/D ratio was reported by [5] in their experimental study.

5. Summary and conclusions

The deformation behavior of copper alloys ultra-thin sheets was investigated with phenomenological plasticity and CPFEM models in the framework of micro-forming. The CPFEM model was more robust with respect to parameter identification. The springback predictions of the CPFEM model were highly sensitive to the assumption made on elasticity (isotropic or anisotropic). Moreover, increasing the number of grains in the sheet thickness led to more springback amplitude and to converging predictions with the phenomenological models in terms of stress fields and springback angle.

References

[1] Peirce, D., Asaro, R.J., Needleman, A., An analysis of nonuniform and localized deformation in ductile single crystals, Acta Metall. 30 (1982), 1087-1119

[2] Raphanel, J., Ravichandran, G., Leroy, Y., Three-dimensional rate-dependent crystal plasticity based on Runge-Kutta algorithms for update and consistent linearization, Int J Solids Struct 41 (2004) 5995-6021

[3] Bron, F. and Besson, J., A yield function for anisotropic materials Application to aluminum alloys, Int. J. Plasticity 20 (2004) 937-963

[4] Cailletaud, G., Pilvin, P., Identification and Inverse Problems: A Modular Approach, ASME Applied Mechanics Division - Publications - AMD 168 (1993) 33

[5] Jiang, C.P., and Chen, C.C., Grain Size Effect on the Springback Behavior of the Microtube in the Press Bending Process, Materials and Manufacturing Processes 27 (2012) 512-518